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UV/H α Turmoil

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Abstract. A great deal of our understanding of star formation in the local universe has been built upon an extensive foundation of H α observational studies. However, recent work in the ultraviolet (UV) with GALEX has shown that star formation rates (SFRs) inferred from H α in galactic environments characterized by low stellar and gas densities tend to be less than those based on the UV luminosity. The origin of the discrepancy is actively debated because one possible explanation is that the stellar initial mass function is systematically deficient in high mass stars in such environments. In this contribution, we summarize our work on this topic using a dwarf galaxy dominated sample of ~ 300 late-type galaxies in the 11 Mpc Local Volume. The sample allows us to examine the discrepancy between H α and UV SFRs using a statistical number of galaxies with activities less than $0.1 M_{\odot} \text{ yr}^{-1}$. A range of potential causes for such an effect are reviewed. We find that while the IMF hypothesis is not inconsistent with our observations, alternate explanations remain that must be investigated further before a final conclusion can be drawn.

1. The Original Motivation for this Study: Probing Starbursts in Dwarf Galaxies

Since the late 70's and early 80's, a time when a number of foundational papers on the measurement of star formation in external galaxies were published (e.g., Kennicutt 1983; Gallagher et al. 1984), the most common way of tracing star formation in nearby dwarf galaxies has been through the H α emission line. And since that time, observations of apparently isolated dwarf galaxies undergoing starburst activity have raised the question of whether the star formation histories of low-mass systems are more generally characterized by bursts rather than modes that are quiescent and continuous (e.g., Gallagher & Hunter 1984; Hunter & Elmegreen 2004; Lee et al. 2009b).

An opportunity to investigate this question in a new way came with the launch of the GALEX satellite (Martin et al. 2005), which enabled sensitive imaging of the far ultraviolet emission (FUV; $\sim 1500 \text{ \AA}$) from hundreds of dwarf galaxies in the nearby

universe (Gil de Paz et al. 2007; Lee et al. 2010). In combination with $H\alpha$ measurements for a complete sample of galaxies, constraints on the average duration, frequency and amplitude of starburst episodes in the population can be computed, since the star formation timescales probed by the two tracers flank their expected duration (i.e., on the order of a dynamical time, roughly 10^8 yrs). To review, $H\alpha$ nebular emission arises from the recombination of gas ionized by the most massive O- and early-type B-stars ($M_* \gtrsim 17M_\odot$). It therefore traces star formation over the lifetimes of these stars, which is on the order of a few million years. In contrast, the UV flux primarily originates from the photospheres of a wider range of O- through later-type B-stars ($M_* \gtrsim 3M_\odot$), and thus measures star formation averaged over a longer $\sim 10^8$ yr timescale.

Qualitatively, galaxy populations with predominantly bursty (or otherwise discontinuous) star formation histories should imprint a clear signature on the distribution of $H\alpha$ -to-FUV flux ratios. Relative to populations where the activity is generally continuous, the average $H\alpha$ -to-FUV ratio should be depressed. When the SFR is constant, the ratio assumes an equilibrium value when the birth of stars responsible for the FUV and $H\alpha$ emission balance their deaths. Variations in the SFR over timescales on the order of ~ 100 Myr disrupt this equilibrium. In the time following a burst of star formation, a deficiency of ionizing stars develops as they expire relative to lower-mass, longer-lived B-stars that produce significant amounts of UV emission, and the $H\alpha$ -to-FUV flux ratio thus is lower (e.g., Sullivan et al. 2000; Sullivan et al. 2004; Iglesias-Páramo et al. 2004). For predominantly bursty populations, determinations of the SFR based on standard linear conversions between the luminosity and the SFR (e.g., Kennicutt 1998; hereafter K98) should also find that the $H\alpha$ -based SFRs tend to be lower than those computed from the FUV, since the conversions are derived under the assumption of constant star formation.

Previous UV studies reported hints of such a trend for low luminosity galaxies, and tentatively attributed it to a systematic increase in the prevalence of bursts in the recent SFHs of dwarf galaxies (Bell & Kennicutt 2001). However, deviations from the expected ratio as a function of luminosity began to appear only when integrated SFRs less than about $0.1 M_\odot \text{ yr}^{-1}$ were probed (i.e., a few times lower than the SFR of the Large Magellanic Cloud), and just handfuls of galaxies with such low activities were included in prior work. Thus, our original objectives were to examine whether the trend persisted with an unbiased, statistical sample of star forming dwarf galaxies, and if so, to use the average $H\alpha$ -to-FUV ratios to produce new constraints on the temporal variability of the integrated activity.

Analysis with our dataset indeed revealed that the dwarf galaxies had systematically lower $H\alpha$ -to-FUV values than more luminous, higher surface brightness spiral galaxies. This seemed to confirm earlier suggestions of generally bursty star formation in low mass systems, and standard population synthesis modeling showed that bursts which elevate the SFR of galaxies by a factor of $\gtrsim 100$ for a 100 Myr duration would reproduce the observed ratios. However, such large amplitudes appeared to be in conflict with other independent determinations of the recent star formation history (SFH), which showed that more modest enhancements (factor of ~ 5) were typical. We therefore were led to consider a wider range of potential causes for the low observed $H\alpha$ -to-FUV ratios in dwarf galaxies. Here, we distill the main points of our analysis, as reported in Lee et al. (2009a). Discussion of this topic also appears in a number of other contributions in these Proceedings, by Meurer; Boselli et al.; Eldridge; Johnson; Calzetti; and Pflamm-Altenburg; among others.

2. Data

Our study is based upon data collected by the GALEX 11HUGS (11 Mpc H α UV Galaxy Survey) and Spitzer LVL (Local Volume Legacy) programs. The sample is dominated by dwarf galaxies, and is thus ideal for studying the nature of systems with low SFRs. Integrated H α , UV, and mid- to far-IR flux catalogs are published in Kennicutt et al. (2008), and Lee et al. (2010), Dale et al. (2009), respectively. Details on the sample selection, observations, photometry, and general properties of the sample are provided in those papers. A brief summary of the dataset is given here.

Our total Local Volume sample contains 436 objects. Galaxies are compiled from existing catalogs (as described in Kennicutt et al. 2008), and the selection is divided into two components. The primary component of the sample aims to be as complete as possible in its inclusion of known nearby star-forming galaxies within given limits. It consists of spirals and irregulars brighter than $B = 15$ mag within 11 Mpc that avoid the Galactic plane ($|b| > 20^\circ$). These bounds represent the ranges within which the original surveys that provided the bulk of our knowledge on the Local Volume galaxy population have been shown to be relatively complete, while still spanning a large enough volume to probe a representative cross section of star formation properties. The secondary component of the sample consists of galaxies that are within 11 Mpc and have available H α flux measurements, but fall outside one of the limits on brightness, Galactic latitude, or morphological type. It is a composite of targets that were either observed by our group as telescope time allowed, or had H α fluxes published in the literature. Subsequent statistical tests, as functions of B-band apparent magnitudes and HI fluxes (compiled from the literature), show that the subset of galaxies with $|b| > 20^\circ$ is relatively complete to $M_B \lesssim -15$ and $M_{HI} > 2 \times 10^8 M_\odot$ at the edge of the 11 Mpc volume (Lee et al. 2009b).

Through a combination of new narrowband H α + [NII] and R -band imaging, and data compiled from the literature, integrated H α fluxes are available for over 90% of the total sample. The new narrowband imaging obtained by our group was taken at 1-2 m class telescopes in both hemispheres, and reached relatively deep point source flux and surface brightness limits of $\sim 2 \times 10^{-16}$ ergs cm $^{-2}$ s $^{-1}$ and $\sim 4 \times 10^{-18}$ ergs cm $^{-2}$ s $^{-1}$ arcsec $^{-2}$, respectively.

Subsequent GALEX UV imaging primarily targeted the $|b| > 30^\circ$, $B < 15.5$ subset of the sample. The more restrictive latitude limit was imposed to avoid excessive Galactic extinction and fields with bright foreground stars and/or high background levels for which observations would be prohibited due to GALEX's brightness safety restrictions. Deep, single orbit (~ 1500 sec) imaging was obtained for each galaxy, following the strategy of the GALEX Nearby Galaxy Survey (Gil de Paz et al. 2007). GALEX observations for a significant fraction of the remaining galaxies beyond these limits were also taken by other GI programs. Overall, GALEX data are available for $\sim 90\%$ of the sample.

Finally, Spitzer IRAC mid-infrared and MIPS far-infrared imaging was also obtained for the $|b| > 30^\circ$, $B < 15.5$ subset of the sample through the Local Volume Legacy program. The far-infrared photometry provide attenuation corrections for our analysis.

3. Results

Our main results are shown in Figures 1 and 2. Figure 1 plots the FUV luminosity against the $H\alpha$ luminosity, while Figure 2 shows the $H\alpha$ -to-FUV flux ratio as a function of the $H\alpha$ luminosity. A systematic decrease in the $H\alpha$ -to-FUV ratio with decreasing luminosity is evident. At high SFRs ($\gtrsim 0.1 \text{ M}_\odot \text{ yr}^{-1}$), the ratio is constant, and the value of $\text{SFR}(H\alpha)/\text{SFR}(\text{FUV})$ is ~ 0.75 . Within the uncertainties, this value is consistent with a zero offset from the expected equilibrium value for constant star formation. However, by SFRs of about $0.003 \text{ M}_\odot \text{ yr}^{-1}$, the average $H\alpha$ -to-FUV flux ratio is lower by a factor of two, and at the lowest SFRs probed ($10^{-4} \text{ M}_\odot \text{ yr}^{-1}$), the average deviation is about a factor of ten.

Best-effort attenuation corrections have been applied to the values plotted in Figures 1 and 2 (i.e., based on Balmer decrements and total infrared to FUV ratios when available, and on empirical scaling relationships otherwise). However, the trend is already evident prior to these corrections; it thus should be robust to the effects of dust since the FUV should be more severely attenuated than the nebular $H\alpha$ emission.

4. Understanding the Systematic Decline in $L(H\alpha)/L(\text{FUV})$

Again, our analysis confirms previous indications of systematically lower $H\alpha$ -to-FUV ratios in dwarf galaxies based on small datasets (~ 20 galaxies with SFRs $\lesssim 0.1 \text{ M}_\odot \text{ yr}^{-1}$), and improves the sampling of this regime by an order of magnitude. Our result is also corroborated by a number of concurrent, independent studies (though with fewer numbers of dwarfs), and the trend has also been reported as a function of decreasing optical surface brightness and stellar mass (Meurer et al. 2009; Hunter et al. 2010; Boselli et al. 2009).

As discussed above, our initial assumption was that such a trend would be an indication of an increased frequency of starburst activity in the dwarf galaxy population, and that modeling the decline of the average ratio would yield new constraints on the characteristic durations, frequencies and amplitudes of the bursts. Examination of a Starburst99 model grid spanning a range of burst parameters computed by Iglesias-Páramo et al. (2004) showed that the factor of two offset observed at $\text{SFR} \sim 0.003 \text{ M}_\odot \text{ yr}^{-1}$ could be reproduced by bursts with amplitudes of $\gtrsim 100$ lasting for 100 Myr. However, such large amplitude bursts appear to be in conflict with other observational constraints. The most direct constraints are provided by studies which reconstruct star formation histories from resolved observations of stellar populations in nearby low-mass systems (e.g., Weisz et al. 2008; McQuinn et al. 2009; McQuinn et al. 2010). The typical burst amplitudes found in such studies range from a few to ~ 10 , an order of magnitude smaller than the factor of 100 bursts required by the models to depress the $H\alpha$ -to-FUV flux ratios by a factor of two. The 11HUGS sample itself also provides a statistical constraint on the average dwarf galaxy starburst amplitude via the ratio of fraction of star formation (as traced by $H\alpha$) concentrated in starbursts to their number fraction (Lee et al. 2009b). The high degree of statistical completeness of 11HUGS makes this calculation possible for galaxies with $M_B < -15$, and again, the burst amplitude is found to be relatively modest (~ 4).

We were thus led to consider a wider range of explanations for the trend, the most viable of which are:

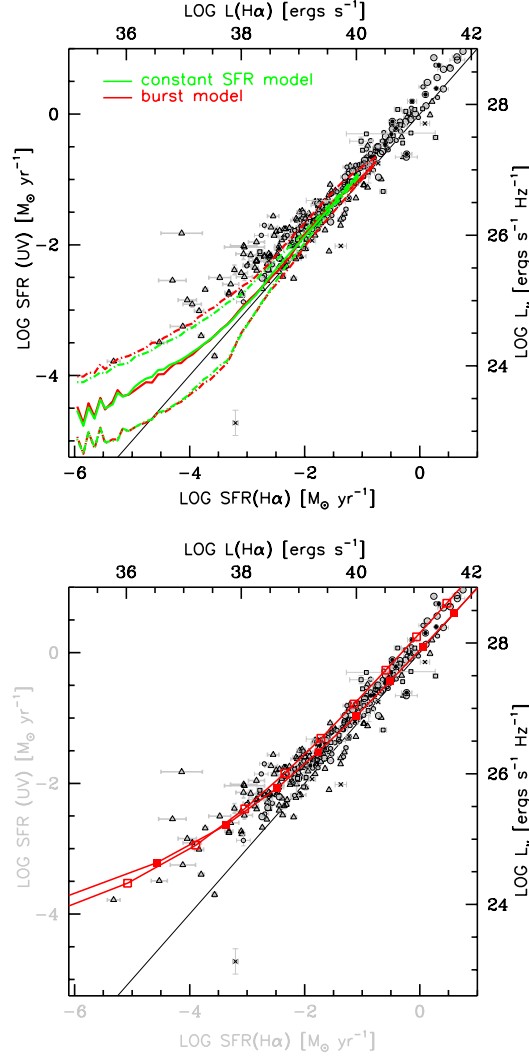


Figure 1. Comparison of FUV and H α luminosities (corrected for internal dust attenuation), with axes indicating the corresponding H α and FUV SFRs, computed from the linear conversion recipes of K98. The solid line represents a one-to-one correspondence between the SFRs. The top panel shows the data with predictions from models which perform population synthesis by random sampling of the IMF (Tremonti et al. 2007). The median-predicted values (solid line) are shown along with values at the 2.5 and 97.5 percentile points (dotted lines). Predictions from IGIMF model of Kroupa & Weidner (2003), as computed by Pflamm-Altenburg et al. (2007) are shown with the data in the bottom panel. The bottom and left hand axes are shown in gray to signify that the K98 SFR scales would not be valid at low SFRs under the assumptions of the IGIMF model.

(1) a leakage of ionizing photons from the low density environments which are characteristic of the galaxies where low H α -to-FUV ratios are observed;

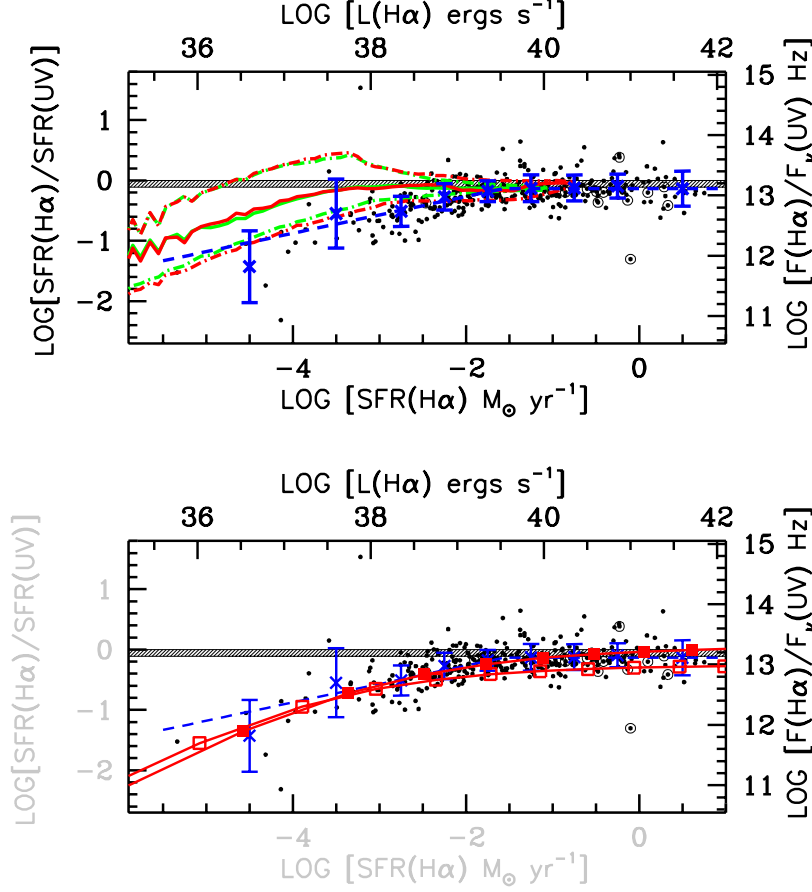


Figure 2. Analogous to Figure 1, but for the ratio of H α -to-FUV SFRs/luminosities (corrected for internal dust attenuation) as a function of the H α SFR/luminosity. The shaded band represents the range of H α -to-FUV ratios predicted by commonly used stellar population models for constant star formation. The dashed line shows a linear least squares fit to the data. Circled points represent galaxies where the H α flux may be underestimated because the narrowband imaging did not wholly enclose the galaxy. The top panel shows the deviations expected from random sampling of the IMF, while the bottom panels shows the predictions of the IGIMF model.

- (2) low probabilities of forming ionizing stars when the integrated SFR of a galaxy is low;
- (3) an IMF which is systematically deficient in the highest mass stars in low density environments.

The first possibility is notoriously difficult to observationally constrain, though the few existing studies of Lyman continuum escape from present-day galaxies have all found upper limits $\lesssim 10\%$ (e.g., Leitherer et al. 1995; Bergvall et al. 2006). These detection experiments have been performed on starbursting galaxies where leakage is thought to most likely occur. Although it is difficult to conclusively rule out this possi-

bility, given the reported upper-limits, it seems improbable that ionizing photon losses could approach the levels required to explain the factor of two discrepancies observed, particularly in the quiescent, gas rich dwarfs that dominate our sample.

A related explanation is that low gas densities lead to extremely diffuse H α emission that falls beneath the detection threshold of standard narrowband observations (Hunter et al. 2010). In this case, the ionizing photons travel far from their parent HII regions, but do not to escape the galaxy entirely. To check whether this could be an issue for our data, we performed the following simple calculation. The potentially missing H α luminosity is computed assuming that the H α star formation rate (SFR) should be consistent with the SFR inferred from the UV continuum flux. The surface brightness of this emission is then estimated with the additional assumption that the nebular flux is uniformly distributed over the area of the UV disk. We found that, under these assumptions, the missing H α should have been unambiguously detected in our observations. However, if the nebular emission instead extends to twice the area of the UV disk (this generally encloses the periphery of the HI gas distribution, and thus serves as a limiting case), then the emission will fall below our sensitivity limits. This issue is one that requires further examination. To do this, we recently obtained deep narrowband ($\sim 8\text{\AA}$) imaging of a few dwarf galaxies with the Maryland-Magellan Tunable Filter on the Inamori Magellan Areal Camera and Spectrograph (IMACS) at the Magellan 6.5m. The data will allow us to observe H α down to $\sim 4 \times 10^{-18} \text{ ergs s}^{-1} \text{ cm}^{-1} \text{ arcsec}^{-2}$ — sensitive enough to detect the surface brightnesses expected if the “missing H α ” is in fact spread over the entire area of the gas disk.

The second possibility is that random sampling of a universal IMF in the regime of ultra-low integrated SFRs, may lead to an apparent deficiency or absence of H α , even when there is on-going star formation, because the probabilities of forming high-mass ionizing stars are low. We use Monte Carlo simulations to model the impact of such stochasticity on the H α -to-FUV flux ratio, and compare the results to the data in the top panels of Figures 1 and 2. The median-predicted values (solid line) are shown along with values at the 2.5 and 97.5 percentile points (dotted lines). While stochasticity clearly does have an effect, its impact does not appear to be large enough to explain the observed trend by itself.

Finally, we also considered the possibility that the IMF is systematically deficient in the highest mass stars in the low density environments of dwarf galaxies. In particular, we compare the model of the Integrated Galactic IMF (IGIMF; Kroupa & Weidner 2003; also see Pflamm-Altenburg; and Weidner, in these Proceedings) to the data in the bottom panels of Figures 1 and 2. The model assumes that the most massive star that can form depends on its parent cluster’s mass in a deterministic (rather than a probabilistic) manner, while the mass of the most massive cluster that can form is dependent on a galaxy’s integrated star formation rate. This model is able to reproduce the trend observed in our data.

5. Discussion and Next Steps

While the consistency between the IGIMF model and the data is intriguing, alternate explanations have not yet been explored to the point where they can be conclusively eliminated. Clearly, the true fate of the ionizing photons in low density gas will be difficult to determine, though we hope that our new ultra-deep tunable filter imaging

will provide new insight on this issue. There was general consensus at the meeting that this must be investigated further.

Whether the starburst scenario, or some class of fluctuating star formation histories, can be ruled out as the cause of the low $H\alpha$ -to-FUV flux ratio was a question that spawned much greater debate (e.g., contributions by Boselli et al. and Meurer in these Proceedings). Our position has been that the modeling of star formation histories warrants further examination, particularly in conjunction with the modeling of stochastic sampling of the IMF. Although we currently find that the large burst amplitudes required to reproduce the trend are in conflict with other observational constraints, stochasticity may amplify the effects of bursty or non-uniform "flickering" SFHs on the $H\alpha$ -to-FUV ratio, and reduce the required amplitudes. Fortunately, a new generation of stellar population synthesis models that incorporate random sampling of a standard IMF has been recently developed by several groups (e.g., see contributions by Eldridge; Fumagalli; and Cerviño in these Proceedings). Such models are much better suited for probing the properties of systems where the IMF may not be fully sampled, compared to existing models such as Starburst99 which use fully-populated $\sim 10^5 M_\odot$ quanta as the basis for the synthesis. Overall, it seems possible that some combination of all of the effects described above may conspire to produce the observed systematic.

Although the origin of the trend is currently unclear, there is one reasonable conclusion that can be drawn from our study: that FUV luminosities provides more accurate SFRs for individual galaxies with low total SFRs and low dust attenuations. The FUV emission should be less prone to stochastic effects from sparse sampling of the upper end of the IMF, and to possible uncertainties in the fate of ionizing photons. With the demise of the GALEX FUV detector however, there is no longer a facility capable of obtaining such data, and for the foreseeable future, new measurements of the SFR in dwarf galaxies will need to be based on $H\alpha$ emission. The role of the new stochastic stellar population synthesis models is thus critical, as they will be necessary to interpret the most likely value and possible range of the SFR that a given $H\alpha$ luminosity corresponds to.

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